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Flow-Control Systems Proof of Concept for Snowmelt Runoff at McMurdo Station, Antarctica

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Abstract

The snowmelt runoff during the austral summer at McMurdo Station is diurnally and seasonally variable. The variability is caused by a dynamic process in which the flow fluctuates daily and seasonally in response to solar and temperature input, melting the snow and glacier ice in the watershed. The current state of drainage at McMurdo Station has operational challenges and environmental impact when incidents of extreme flow occur. A surge of massive amounts of runoff downstream overwhelms both the drainage-system capacity and operational personnel and mobilizes sediments and transports potential and known contaminants downstream.

The purpose of this project was to demonstrate the feasibility and use of flow-control systems (including wooden and rock weirs) to attenuate flow in drainage channels and digging settling basins to contain snowmelt. When runoff was light to moderate, the weirs performed well, collecting sediments and attenuating the diurnal flows in the channels. However, the weirs became nonfunctional under high and surge flows. Experimental settling basins were constructed to determine whether they will retain the snowmelt and whether their berm and spillway will hold up and attenuate the flow. Moreover, this report highlights best management practices and lessons learned for sustained elimination of erosion and for reduced drainage-system maintenance.

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Preface

This study was conducted for the National Science Foundation (NSF), Office of Polar Programs (OPP), under Engineering for Polar Operations, Logistics, and Research (EPOLAR) EP-ANT-15-04, "Drainage Solutions Implementation." The logistical guidance and technical supervision were provided by Margaret Knuth (program manager), NSF-OPP, U.S. Antarctic Program.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Sarah Kopczynski was Chief, CEERD-RRH, and Janet Hardy was the program manager for EPOLAR Antarctica. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen, and the Director was Dr. Robert Davis.

The implementation of these drainage solutions would not have been possible without assistance and support from Antarctic Support Contract staff, including Ryan Wallace; Robert DeValentino, William Ames (former staff), Dale Rivers, Tyonek McAdams (former staff), Megan Whitmore, Thomas Verville, and Corey Biddle (former staff). The authors are grateful for the assistance provided by shipping, receiving, supply, and logistics support at McMurdo Station during the fieldwork.

The authors also thank the following CRREL staff for their contributions: Charles Smith, Terry Melendy, and Andrew Bernier for acquiring the supplies and for sawing and framing the pieces of the wooden weirs; Meredith Carr (former CRREL) for technical support; Renee Melendy for superb office-administrative and logistical support; and Joni Quimby for shipping and receiving the equipment and supplies used during the field work.

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COL Bryan S. Green was Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

Acronyms and Abbreviations

$ATDD_{net}$	Net Accumulated Thawing Degree-Days
BMP	Best Management Practice
CRREL	Cold Regions Research and Engineering Laboratory
EPOLAR	Engineering for Polar Operations, Logistics and Research
ERDC	U.S. Army Engineer Research and Development Center
NSF	National Science Foundation
O&M	Operations and Maintenance
OPP	Office of Polar Programs
SOP	Standard Operating Procedure
USDA	U.S. Department of Agriculture
WQB	Winter Quarters Bay

Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
gallons (U.S. liquid)	3.785412 E-03	cubic meters

Executive Summary

The McMurdo Station watershed extends from the perennial snow and ice fields north of the Station down to McMurdo Sound. Runoff from the watershed results almost exclusively from snowmelt, which passes through McMurdo via a system of drainage ditches, gullies, and culverts. Ultimately, the snowmelt is discharged to Winter Quarters Bay and McMurdo Sound through several points. The drainage system at McMurdo Station was not holistically designed and was constructed on an ad hoc basis as the Station has developed over the last 50. In some summers, the seasonal runoff can be extreme where the flow can overwhelm both the drainage system and the operations and maintenance (O&M) crew.

CRREL has been involved in assessing the drainage problems and characterizing the runoff at McMurdo Station. Our investigations encompassed measuring the snowmelt runoff at the Station in 2009–10 and 2010–11, characterizing the watershed and the critical parameters that influence the runoff, and measuring the pollutants in the runoff. Our study continued by designing flow control systems, identifying mitigation measures and standard operating procedures to mitigate drainage and sediment erosion issues and the accumulation of ice and snow in drainage channels.

This report highlights our austral summer 2015–16 demonstration results on the feasibility and use of flow-control systems, including testing (temporary and portable) wooden and rock weirs, digging settling basins to capture the snowmelt runoff in major subbasins, and capping selected culverts' inlets after flow stops at the end of summer to minimize ice buildup during winter months. In addition, we incorporated lessons learned and current practices used by O&M staff and identified appropriate BMPs for operation and maintenance of the drainage system.

Construction and installation of the temporary weirs were simple and required minimal time to construct. The weirs performed well when flows were light to moderate, collecting sediments and attenuating the diurnal flows. In the morning of 18 December, a continuous surge of flow occurred; and massive amounts of water surged downstream. The weirs were structurally stable and held during a significant flow surge; weirs were considered nonfunctional under high and surge flows and failed when excess flow eroded the banks adjacent to weirs and the weirs became submerged.

Digging the two adjacent ponds at site 3C was achieved with the use of the excavator. The total capacity was significantly smaller than the minimum design for Site 3C by a factor 15. The reasons for the limitations included insufficient space to build the designed size, availability limitations for the equipment, and the unstable ground created safety concerns for the equipment (sliding and traction) and operator if dug deeper. However, the ponds built at site 3C will serve as experimental settling basins to determine whether the ponds will retain the snowmelt and whether the berm and spillway will hold up and attenuate the flow. They will also be used to assess the seasonal ice buildup in the ponds.

The combination of steep slopes, lack of vegetation, an impervious permafrost layer below the active (thawed) layer, and no structural support makes banks prone to erosion during excessive snowmelt runoff. Our study suggests that banks along the main channels should be stabilized and lined using gabion (where the rocks are reinforced with wires) or geosynthetics and covered with big stones and rocks to mitigate this problem.

Based on our observation, current drainage practices used by O&M staff has gained a few improvements; this included their attentiveness in ensuring that the heat-trace systems were working and that the culverts had openings for flow and their willingness to install rock weirs (again) this summer (2016–17). The Standard Operating Procedure (SOP) by Affleck and Carr (2014) highlighted recommendations, such as digging out culvert inlets and outlets by mid-November; removing the ice or debris in culverts before the first week of December; clearing blockages in tight areas with intercepting utilities; replacing undersized and aging culverts; plugging the ends of the culverts with an actual cap before winter hits; and using appropriate BMPs for operation and maintenance of the drainage system. We believe that adopting the SOP and BMPs requires stakeholder (National Science Foundation and Antarctic Support Contract) buy-in and designated and timely commitment of resources (equipment and staff). The SOP, BMPs, and lessons learned should continue to evolve or improve and be incorporated into the proposed redevelopment at McMurdo Station as part of sustainable practices.

1 Introduction

The drainage system at McMurdo Station was not holistically or appropriately designed and was constructed on an ad hoc basis as the Station developed over the last 50 years. In some years, the seasonal runoff can be extreme where the flow exceeds the drainage-channel capacity and overflows, overwhelming both the drainage system and the operations and maintenance (O&M) crew. Another concern is that elevated pollutant levels are transported in the runoff. At the request of the National Science Foundation, the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has been quantifying the runoff and investigating the drainage and erosion problems (Affleck et al. 2014a, 2014b, 2014c, 2012a, 2012b; Affleck and Carr 2014, 2015) to provide solutions to attenuate the runoff and to minimize erosion.

1.1 Background

The McMurdo Station watershed is one of the southernmost basins that annually experiences active water flow from snowmelt (Figure 1). The watershed is divided into six basins (Figure 2). Three major subbasins (1, 2, and 3) are located north of the Station and are largely covered with a perennial snow and glacial-ice cover. The other three subbasins (5, 6, and 7) are relatively small. Subbasin 1 drains the area from the west along Hut Point Ridge and Arrival Heights, then along the road and down to the ice pier and Hut Point. Subbasin 2 has the largest area and encompasses the majority of the snowfield and the depression above Gasoline Alley. Subbasin 3 includes the area north of the Main Road, then adjacent to Crater Hill area, loops around portion of the snowfield, and continues on the east at the T-Site area. Snowmelt runoff from subbasins 2 and 3 merges downstream into Winter Quarters Bay (WQB). Subbasin 5 drains the area around the dorm, along the road towards the bay, and below the Water Treatment Plant. Subbasin 6 is composed of the area south of the dorms and Main Road, along the road to the Chalet, and down to the road along the bay. Subbasin 7 is the area south of the Fuel Tanks, around Observation Hill, and below the Helo Pad.

Figure 1. Map of McMurdo Station showing the watershed boundary (*dashed line*) and ice field contributing to the snowmelt. The watershed covers an area of approximately 5 km^2 (Affleck et al. 2012a).

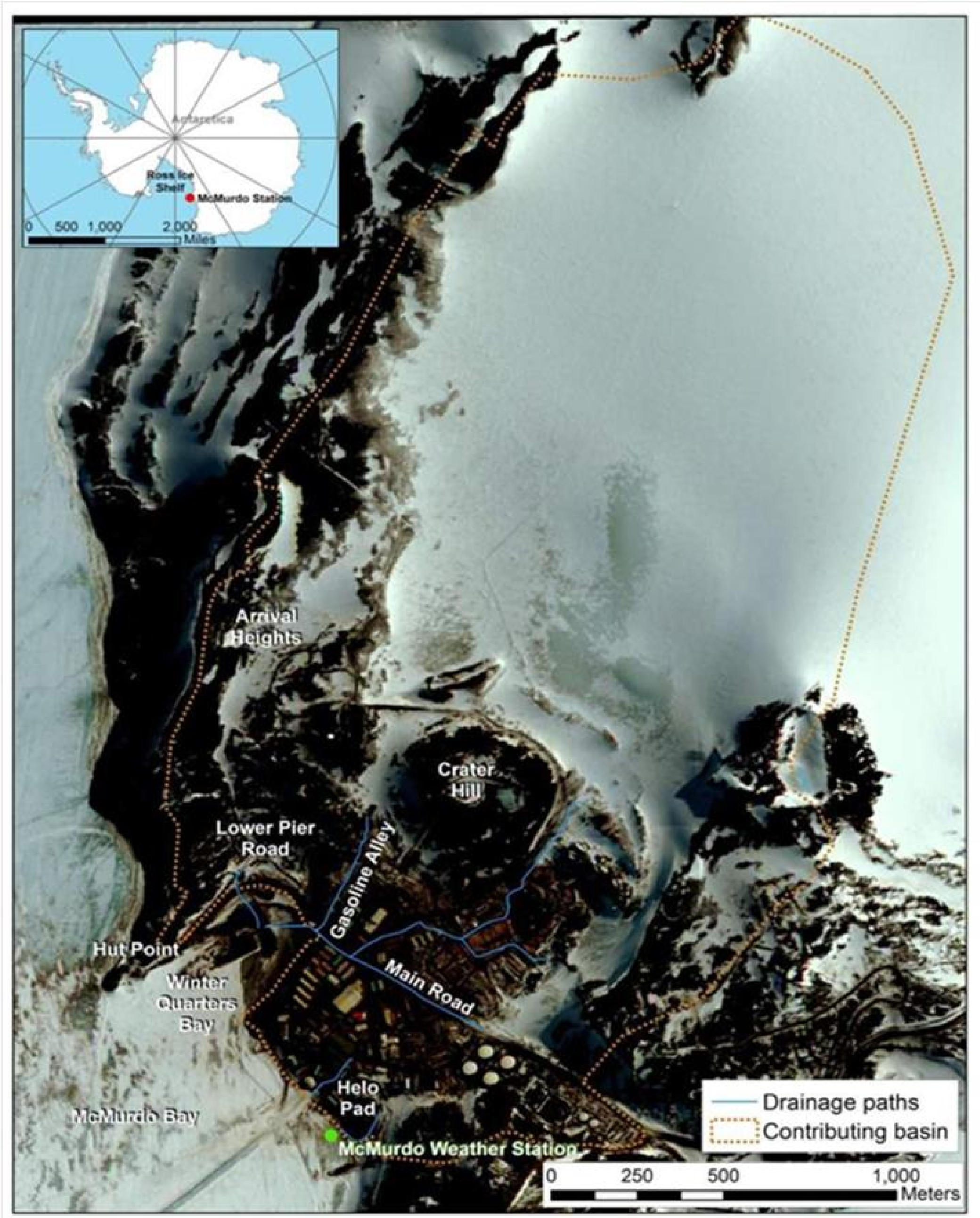
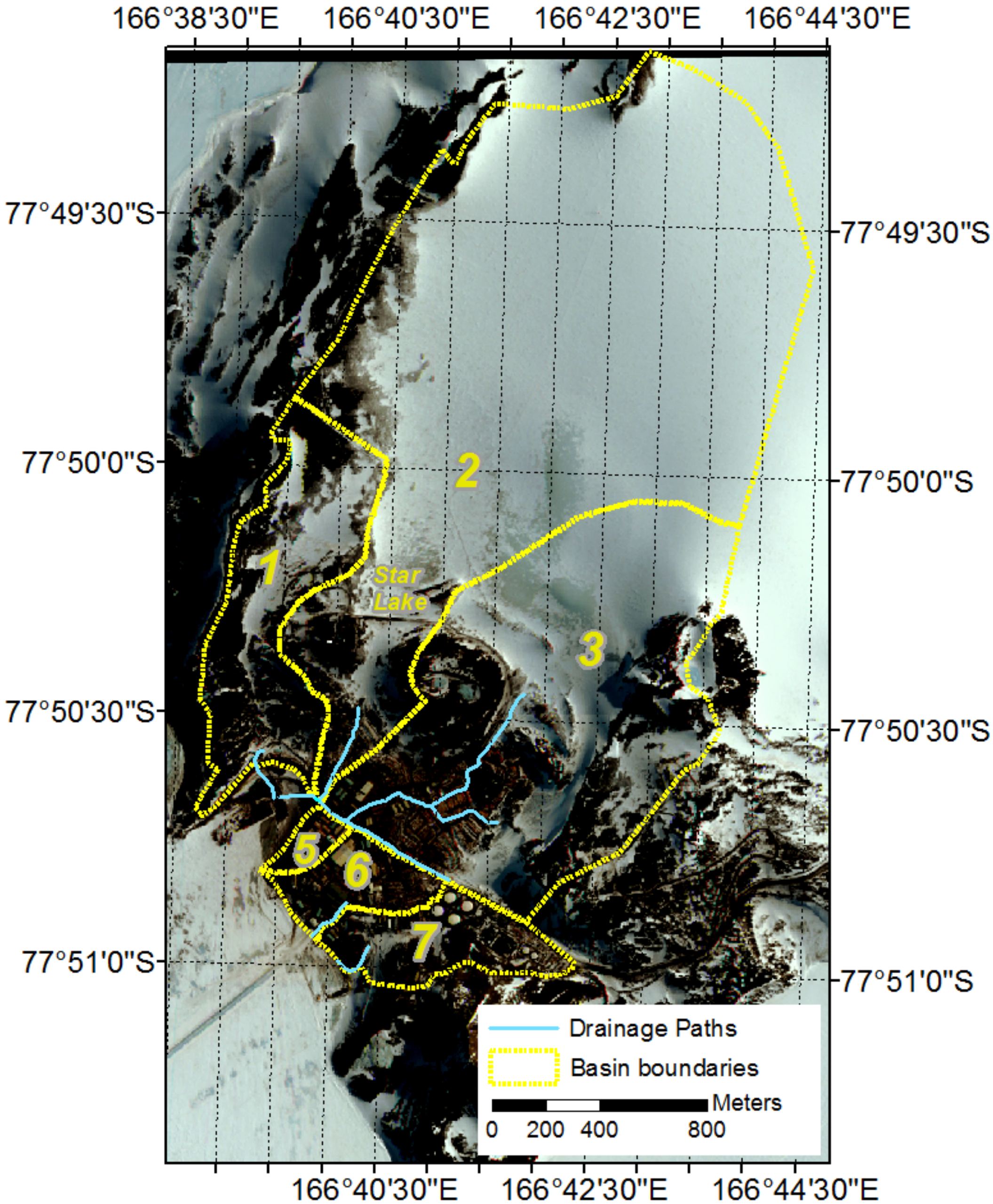


Figure 2. McMurdo Station subbasin boundaries and drainage paths (Affleck et al. 2012a). (Note: there is no subbasin 4.)



As ice accumulates in culverts throughout the winter, O&M staff remove ice in major culverts by melting and flushing the ice with high water pressure. Additionally, controlled blasting (using explosives) has been used to allow mechanical removal of major ice buildup in culverts. In the past four years, heat-trace system have been installed in several culverts to melt the ice that accumulate in the winter months. Some of the heat-trace systems

are connected into buildings, and others are plugged into a generator for power supply before the melt season. During the 2015–16 field season, we observed improvements in practices where O&M staff were proactive and painstakingly attentive to ensure that the heat-trace systems were working and that the culverts had openings for flow, especially early in the season when culverts have more ice in them. However, during this study period, the main culverts were jammed with ice and debris; some culverts still required upgrades and others were undersized.

Most drainage channels were constructed with steep sides or embankment slopes and steep in-channel gradients, causing an increased runoff velocity and channel embankment instability. The erosion problem in McMurdo is somewhat unique, and obvious erosive and depositional features are common in the area. The uniqueness contributing to the erosion problems is due to site conditions, including the steepness of the terrain, steep drainage paths, the lack of vegetation, an impervious permafrost layer below the active (thawed) layer, and the common daily freeze–thaw cycles when runoff occurs during the austral summer.

Given the variability of the snowmelt runoff with extreme flow rates and runoff containing significant concentration of pollutants, application of best management practices (BMPs) and erosion control systems are crucial for reducing sediment transport and for preventing erosion at McMurdo Station (Affleck et al. 2014b).

1.2 Objectives

The purpose of this project was to demonstrate the feasibility and use of flow-control systems based on portability and ease of construction (Affleck et al. 2014c), including the following:

- Testing two sets of flow-control prototypes: wooden and rock weirs
- Digging settling basins to contain snowmelt in major subbasins
- Capping selected culverts' inlets after flow stops at the end of summer to minimize ice buildup during winter months

In addition, this project assessed current practices used by O&M staff that aligned with the implementation of the Standard Operating Procedure (SOP) *Preliminary Guidelines and Standard Operating Procedure for*

Drainage and Erosion Control at McMurdo Station that CRREL developed (Affleck and Carr 2014). The overall goal of this document is to provide guidance to minimize drainage and erosion problems and to incorporate lessons learned and appropriate BMPs for operation and maintenance of the drainage system.

1.3 Approach

BMPs are commonly defined as applications of engineering flow-control measures, schedules of activities, preventions of certain impractical practices, maintenance procedures, and structural or managerial practices that when used singly or in combination will control the runoff and prevent or reduce the release of pollutants to water sources or waterbodies (Affleck et al 2014c). Methods most applicable to McMurdo are those for addressing bare-earth erosion. These methods and practices include steps to control the flow from unprotected sediments, to prevent sediments from moving offsite, and to reduce erosive forces (Tetra Tech 1992). For McMurdo terrain, soil, climate, or steepness conditions, a combination of non-structural and structural systems are feasible methods to use. Non-structural methods include riprap, porous fabric, or geotextiles and for slope reinforcement, filtration, drainage, and erosion control (Tetra Tech 1992). Structural flow controls include any physical alteration in the system that increases stability (USDA 2007a) or reduces the energy available to move sediment.

The main structural controls considered at McMurdo were small weirs or check dams made of loose rock, wood, and other materials. The structures reduce erosion and sediment transport and promote sedimentation and channel stability by slowing velocities, reducing effective slopes, dispersing flow below the dam, and catching and trapping sediment in small pools above the structure (USDA 2007b). Other structural control measures evaluated in this study included the construction of sediment ponds. For McMurdo, the ponds are primarily to store the snowmelt before the runoff flows into the receiving channels. The following sections describe installation and construction of these systems.

1.3.1 Sediment ponds

Ponds detain flow, attenuating the peak and allowing sediment to settle (Ferris 1983). The sediment ponds designed for McMurdo Station were located upstream of drainage paths to capture the snowmelt runoff from subbasins and to control the flow in the channels (Figure 3) (Affleck et al. 2014c). A typical pond would require a riser and outlet pipe; however, the use of a riser and a piped outlet in McMurdo conditions is infeasible due to maintenance requirements from ice accumulation. The design metrics for McMurdo were fully described in Affleck et al (2014c). The sediment ponds were designed to accommodate both water and ice accumulation with the notion that these ponds should be maintain on a regular basis to remove ice and sediment.

Figure 3. Proposed pond locations from Affleck et al. (2014c).

Building a pond or two was planned during austral summer 2015–16 to examine the challenges or limitations in digging the materials by using available equipment. The other challenge for building the ponds was not knowing the subsurface conditions and materials to be dug. Building a pond was an experiment to determine if it could hold snowmelt and attenuate the flow. Pond 3C was the first one to be built during austral summer 2015–16 because it would capture major snowmelt from subbasin 3 and because there was appropriate space for the pond. Pond 2C could potentially be dug if equipment and staff were available and if the location was suitable.

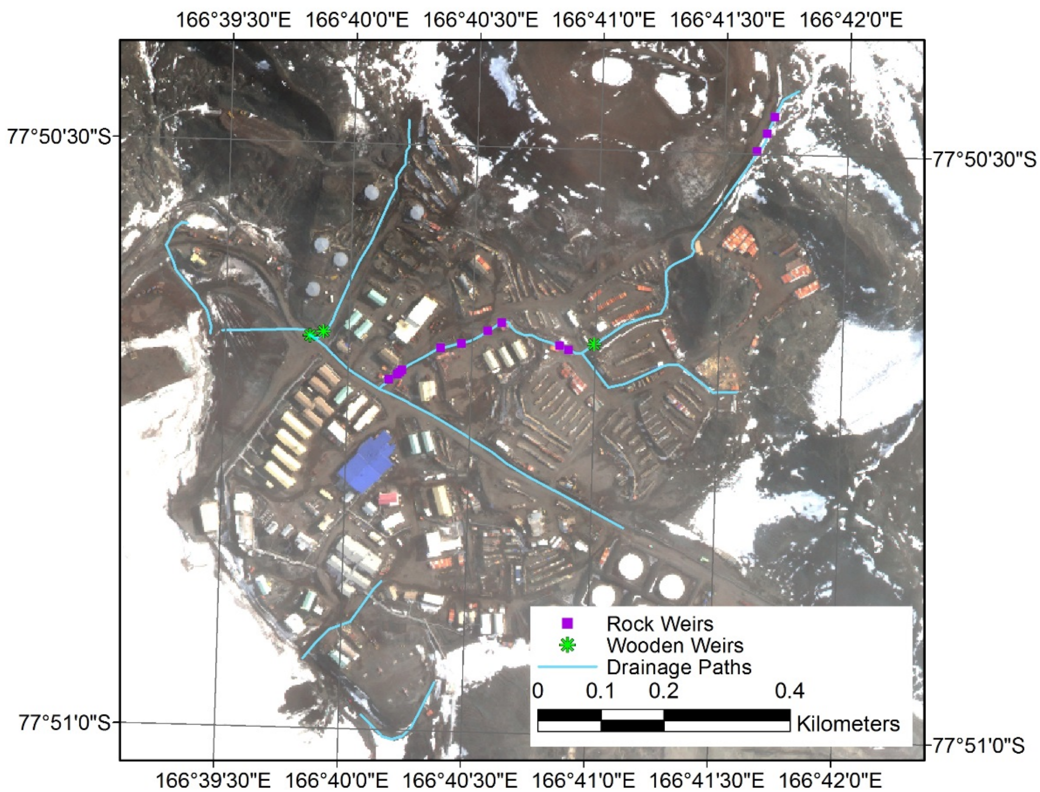
1.3.2 Weirs

Weirs are most commonly used to control upstream erosion and to trap sediment before it enters a receiving water, such as the Bay at McMurdo (Affleck et al 2014c). These structures are designed to have a certain level of porosity to filter sediment and to attenuate the flow rather than just to impound water (Ferris 1983). By releasing part of the flow through the dam, porous materials also decrease the head over the top of the structure, thereby reducing erosion immediately downstream and reducing the force against the structure itself. They are particularly practical at McMurdo because they are very effective for reducing sediment loss in areas where vegetation cannot be established, one of the few common erosion controls that can be effective without vegetation (Boix-Fayos et al. 2008).

Rock and wooden weirs were designed specifically for McMurdo Station drainage channels with the goals of portability; durability; and practicality, including ease of installation and removal each season (Affleck et al. 2014c). Figure 4 shows the actual locations where rock and wooden weirs were installed. Affleck et al. (2014c) discusses in detail the metrics used to evaluate the erosion-control design capabilities of porous weirs. Weirs were structurally designed according to the runoff data on-site and by using environmentally safe materials; design forces of the weirs were calculated, including pressure, uplifting, overturning, shear, and compression. The designs included geotextiles to reduce uplift forces. If the rock weirs were to fail, failure would likely be by breaking apart because of discontinuity of rocks. Calculations showed the likelihood of such failure was unlikely. Wooden weirs were evaluated based on allowable stress and deflection for the wood and the metal post anchors.

For wooden weirs, boards were cut to length; and sections were framed at CRREL before shipping the materials to McMurdo Station. Two sets of installation frames—anchored and unanchored wooden weirs—were fabricated for flexibility and ease of installation. The anchored wooden weirs required inserting the 3 in. diameter metal post 3 ft deep into the ground. The unanchored wooden weirs were designed to set the weir on top of the channel and on an angle.

Figure 4. Actual locations where the wooden and the rock weirs were installed.



1.3.3 Culvert caps

Culverts are prone to ice and snow buildup. Capping the inlets and outlets of the culverts at the end of the summer season when all flow has stopped would minimize the ice and snow accumulation in culverts during the winter months. For this study, rectangular culvert caps were cut from plastic sheeting (i.e., the same high-molecular weight polyethylene material used for traverse sleds). These caps were left for the O&M staff at the Station to install when the flow subsided or stopped and were removed without problem before the snowmelt commenced for austral summer 2016–17.

Though they were expected to allow only minimal ice blockage and snow intrusion in the culverts if the caps were properly installed, when removed, snow intrusion was present in the culverts (DeValentino 2016).

2 Climate and Runoff

Runoff commences as the air temperature gradually rises. Other critical drivers, such as solar gain, also influence the runoff. The daily air-temperature fluctuations at McMurdo depict several warming events occurring during the summer months. The austral summer at the Station varies from year to year as shown in Appendix A. In general, the daily maximum temperature for McMurdo Station revealed that above-freezing temperatures normally commence sometime between mid- to late November and persist to late January or early February (Affleck et al. 2012a, 2014a). Within the last 15 austral summers, the highest number of days with a maximum temperature above freezing (55 days) was during the summer of 2006–07 (Table 1). One of the coldest summers was the summer of 2014–15 with a daily maximum temperature above freezing for only 12 days during the entire summer.

In the 2015–16 austral summer, the first warm spell occurred on 26 November with a daily maximum temperature of 0°C (Figure 5). The daily maximum temperature from the first week of December to mid-December hovered just above 0°C for 7 days. This was then followed by a cooling trend until mid-January when temperature drifted below 0°C. Another warm trend followed from mid-January to the first week of February. Compared to the last 15 austral summers, the temperature during the 2015–16 austral summer was within average. Figure 6 shows the net accumulated thawing degree-days ($ATDD_{net}$), or the cumulative number of degree-days when (average) air temperatures were above 0°C, over several summers. Each time the $ATDD_{net}$ rises, it indicates a warm spell; and the magnitude of the warm spell is indicated by the amplitude of the rise. Based on daily maximum temperature, the thawing periods for each summer during the last 15 years can be summarized in terms of the number of days with a daily maximum temperature above freezing, the length of the summer or thaw season (number of days from first to last days with a daily maximum temperature above freezing), and $ATDD_{net}$ or the magnitude of the thaw season (Table 1).

Table 1. Summary of the thawing periods during the last 15 austral summers based on daily maximum temperatures.

Austral Summer	Number of Days with a Maximum Temperature Above Freezing (days)	Length of Summer or Thaw Season (days)	Net Maximum ATDD (°C-days)	Thawing Period
2000–01	29	97	51.5	11 Nov. 2000–15 Feb. 2001
2001–02	42	85	123.9	27 Nov. 2001–18 Feb. 2002
2002–03	30	57	75.1	06 Dec. 2002–31 Jan. 2003
2003–04	38	87	95.6	09 Nov. 2003–03 Feb. 2004
2004–05	54	95	121.4	12 Nov. 2004–14 Feb. 2005
2005–06	49	71	126.7	27 Nov. 2005–05 Feb. 2006
2006–07	55	75	191.9	23 Nov. 2006–02 Feb. 2007
2007–08	36	60	78.9	24 Nov. 2007–22 Jan. 2008
2008–09	42	60	73.6	08 Dec. 2008–05 Feb. 2009
2009–10	42	86	75.8	15 Nov. 2009–08 Feb. 2010
2010–11	39	81	90.4	10 Nov. 2010–29 Jan. 2011
2011–12	39	100	68	14 Nov. 2011–21 Feb. 2012
2012–13	45	77	83.8	15 Nov. 2012–30 Jan. 2013
2013–14	50	81	124.1	25 Nov. 2013–13 Feb. 2014
2014–15	12	28	17.8	03 Jan. 2014–29 Jan. 2015
2015–16	31	71	47.8	26 Nov. 2015–04 Feb. 2016
Mean	40	76	90.4	
Maximum	55	100	191.9	
Minimum	12	28	17.8	

McMurdo Station had very hot summers in 2006–07, 2012–13, and 2013–14 with $ATDD_{net}$ above 30°C-days (up to 51°C-days on 30 January 2007). A group or cycle of much cooler summers (i.e., $ATDD_{net}$ below 90°C-days) have happened in the last 15 austral summers, including the summers of 2000–01, 2002–03, 2003–04, 2008–09, 2009–10, and 2014–15. Other summers were mostly mild with $ATDD_{net}$ between 10°C-days and 25°C-days (summers of 2001–02, 2004–05, 2005–06, 2007–08, 2010–11, 2011–12, and 2015–16). Considering that 2007–08, 2010–11, and 2015–16 summers were very similar and mild, a strong warm spell early in December and into mid-December (about 15°C-days and 1.5 weeks long) and a shorter, smaller warm spell in mid-January (about 7°C-days and 3–4 days long) contributed to the melting of snow and ice and thus resulted in significant runoff.

Figure 5. Daily maximum, minimum, and average air temperatures at McMurdo Station for austral summers of 2015–16.

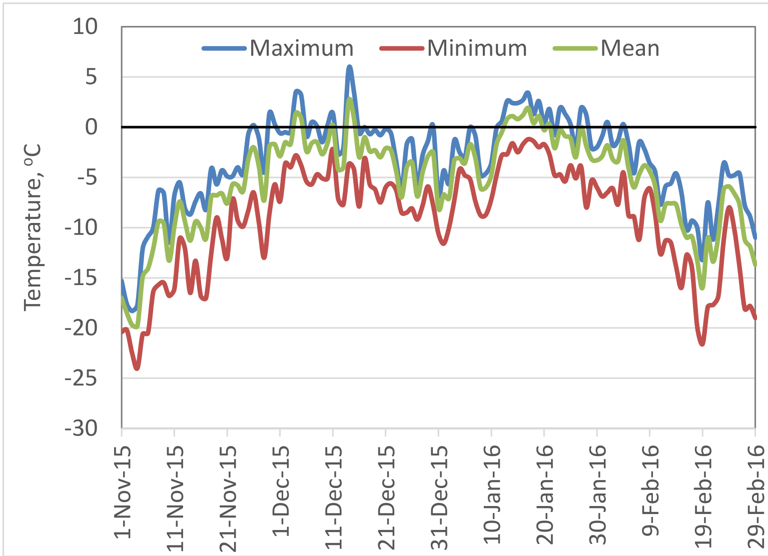
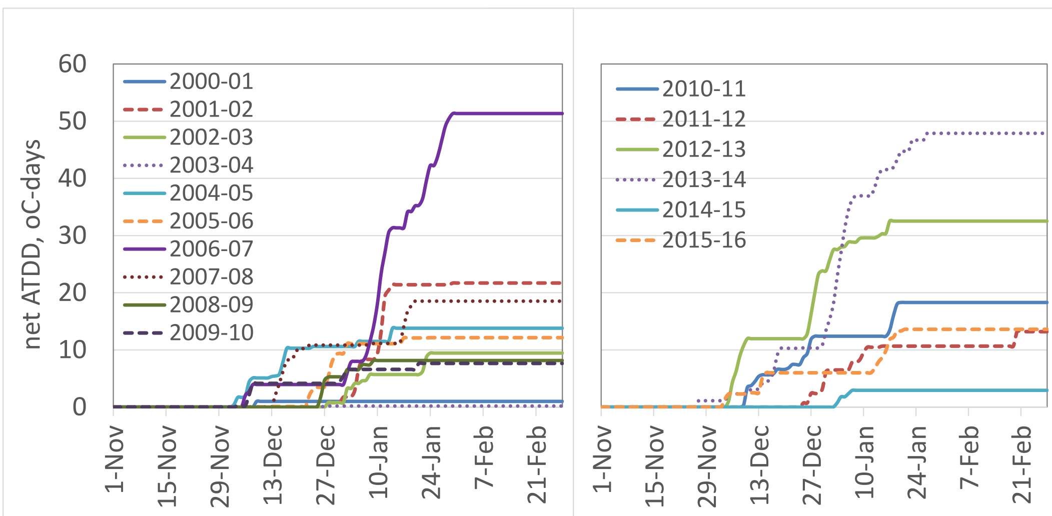


Figure 6. Net accumulated thawing degree-days over several summers at McMurdo.



Predicting when the runoff occurs is critical for operation and maintenance of the channels because snow and ice in the drainage channels are manually cleared to accommodate the impending snowmelt runoff. The predictability for occurrence of peak runoff is influenced not only by air temperature but also by solar gain. Affleck and colleagues (documented in Affleck et al. 2014a and Affleck and Carr 2015) developed a relationship relating the incidences of runoff and peak flow (measured in the summers of 2009–10 and 2010–11) to the maximum temperature and cloud cover. These type of data are collected daily by the McMurdo Weather Station

and can easily be populated into a Microsoft Excel spreadsheet macro developed by Affleck and Carr (2015) to estimate the expected peak flow date for the season. Indicators for air temperature were used based on the date when peak maximum temperature occurred, the start date when the temperature was above freezing for greater than 3 consecutive days, and the corresponding maximum change (Δ_{max}) in $ATDD_{net}$ (in °C-days). The indicator for daily cloud cover is expressed in terms of clearness to represent the solar input. Clearness was evaluated as 100% minus the reported cloudiness (%). Data collected by McMurdo Weather Station for sky cover is expressed from 1 to 8 (1 means clearness is 100%; 8 means clearness is 0%). Clearness was then related to the maximum clearness over the first 3 days above freezing. Lag time is the indicator used to represent the time between peak temperature and peak flow (in days).

Six occurrences when the runoff and peak flow occurred were estimated using the macro for austral summer 2015–16 (Figure 7), correlating with the peak temperature events, Δ_{max} $ATDD_{net}$, and maximum clearness (Table 2). The first peak temperature on 23 November had a maximum clearness over 3 days near 63%; this lag time of 16 days based on Δ_{max} $ATDD_{net}$ indicates that the peak flow would have occurred on or about 9 December. The second peak was estimated to occur on 12 December based on the Δ_{max} $ATDD_{net}$ of 1.7°C-days on 29 November. The range of possible dates for the first peak flow and second peak flow to occur had overlapped because lag times ranged between 10 and 18 days (5 to 14 December for the first peak and 8 to 16 December for the second peak). Although measurement of runoff was not part of the project scope for the summer of 2015–16, we noted the flow conditions in the channels. Steady flow started during the first week of December in channels draining the snowmelt from subbasin 3, and the flow picked up starting on 8 December. The flow from snowmelt in subbasin 3 continued heavily on 14 December until 19 December. On 17 December, the flow along Gasoline Alley from subbasin 2 started picking up; in the morning of 18 December, a continuous surge of flow occurred as a raging river. A culvert connected as an outlet to the upstream (Star Lake, Figure 2) natural pond that collects significant amounts of snowmelt from subbasin 2 finally cleared of ice. The accumulated snowmelt in Star Lake drained on 18 and 19 December, and massive amounts of water surged downstream. The flow then tapered on 20 December as the temperature decreased and cloud cover persisted for days. The subsequent estimated peaks had very low clearness. A diurnal flow between light to

moderate remained from 20 December 2015 to the end of January 2016. The last peak was estimated on 12 February 2016. The flow continued from the end of January to early February 2016 and subsided or stopped around 15 February (Blaisdell 2016).

Figure 7. Lag time between air temperature and flow for drainage channel S2B, austral summer 2007–08.

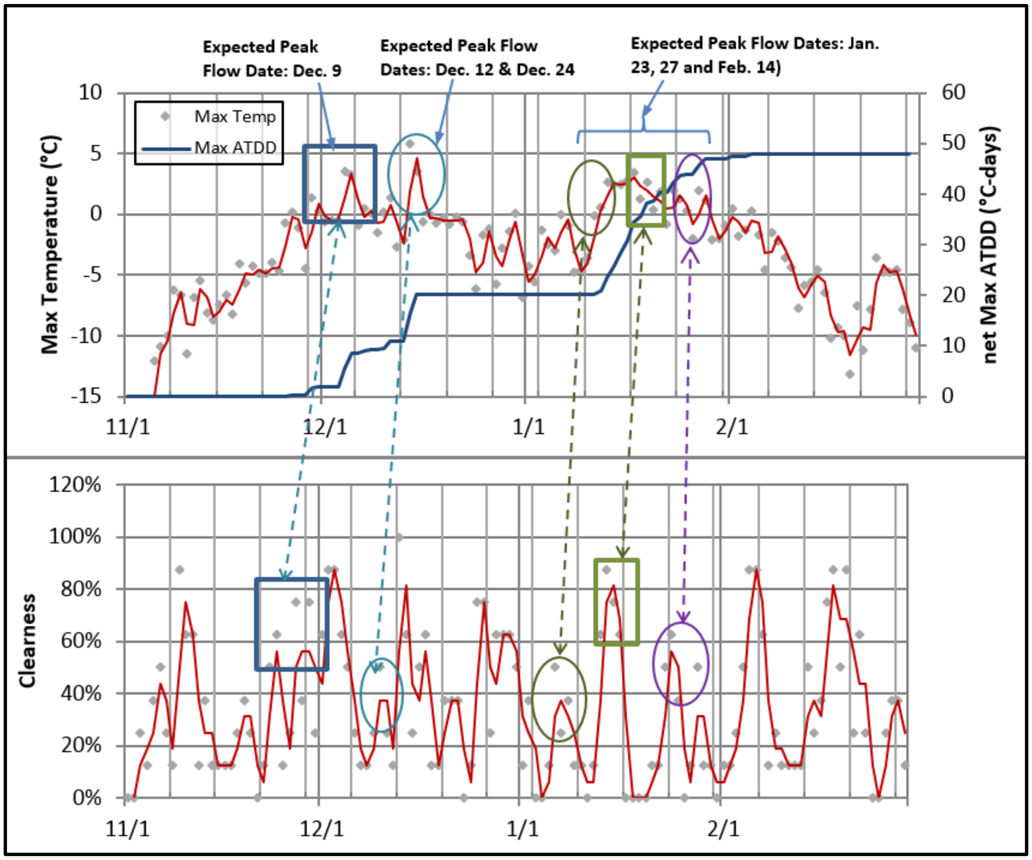


Table 2. Summary of warming events during summer 2015–16.

Date of Peak Temp	Date of Temp > 0°C for 3 days	Max Clearness over 3 days (%)	Δ_{max} $ATDD_{net}$ (°C-days)	Expected Peak Flow Date	Date Ranges for Expected Runoff Duration
11/23	--	62.5	0	12/09	12/05–12/14
11/28	11/29	75	1.7	12/12	12/08–12/18
12/08	12/07	25	0.6	12/24	12/20–12/28
01/07	01/06	50	0	01/23	01/19–01/28
01/17	01/13	87.5	4.7	01/27	01/23–01/31
01/29	01/27	50	0	02/14	02/10–02/19

– indicates that the temperature was below 0°C but that successive days had clearness greater than 50%.

3 Field Proof of Concept

This section describes the installations of the weirs and excavation of the ponds.

3.1 Weirs

As mentioned in Section 1.3.2, the wooden boards were already drilled and cut to length; and some sections were framed or preassembled at CRREL prior to installation. These frames were set up for both anchored and unanchored wooden weirs.

Each anchored wooden weir required drilling four ground holes to insert the 3 in. diameter metal posts 3 ft deep into the ground. Drilling took approximately 4 hours (with one driller) to drill the eight holes for the two sets of anchored wooden weirs. Most of the wooden boards that were cut to length fitted well, but a few needed to be shortened to match the bank angles and surfaces. Attaching the wood onto the metal posts required brackets and screws. Fastening the wood onto the metal posts to create one weir took 2 hours for one person. The first anchored wooden weir was installed on the Main Road, and the edges of the weir were placed diagonally uphill on each of the banks (Figure 8). The second anchored wooden weir was installed along the downstream section of Gasoline Alley (Figure 9) and was placed across the channel, and the edges of the weir were placed straight uphill on each of the banks. Typically, a filter fabric (using filtration geotextile) is placed on the upstream side of a wooden weir. In this case, the filter fabric was not placed because the geotextile was likely to slow down the flow tremendously if a significant flow occurred.

One unanchored wooden weir was built to set on top of the channel and on an angle. The wooden pieces were adjusted to fit the uneven ground and banks; and in some cases, boards were trimmed to fit the angles of the ground (Figure 10). Aside from the boards, assembling the unanchored wooden weir required mainly screws. A filter fabric (using filtration geotextile) was placed on the upstream face of the wooden weirs and was fastened using metal staples. The unanchored wooden weir was installed by two people within 2 hours. A 6 in. layer of rock was piled on the upstream side of the weir to stabilize the entire system.

Figure 8. Prototype anchored wooden weir tested along the main channel.

Figure 9. Prototype anchored wooden weir tested along the channel on Gasoline Alley.

Figure 10. Prototype unanchored wooden weir tested along one of the channels. The *left* photo is the downstream side of the weir. The *right* photo is the upstream side of the weir.

It took between 3 and 4 hours to build all six rock weirs by using an excavator and a loader at the same time. The loader hauled the rocks and dumped the rocks in the selected location in the channels. The channels were previously shaped and cleared of snow and ice early in the season. The weirs used two rock size ranges: 2 to 8 in. rocks (Figure 11) and 8 to 12 in. rocks (Figure 12). Rock weirs using the 2 to 8 in. rocks were constructed along the channel near Building 175 and upstream along Gasoline Alley (Figure 11). The amount of rocks used depended on the width of the channel and the height of the weir. In upstream channels, rock weirs were built using 8 to 12 in. rocks (Figure 12). The height of the rock weirs (i.e., the height from the middle bottom of the channel to the top of the weir) depended on the channel cross section and ranged from 1.5 to 3 ft. A minimum height of 1.5 ft was used for shallow and wide channel. For narrow channels, a 3 ft rock weir height was used. The excavator was used to shape the weir, to compact the rocks, and to create a sump or depression upstream of the weirs.

Figure 11. Rock weir using the 2 to 8 in. rocks. The excavator created a sump upstream of the weir.

Figure 12. Rock weir using 8 to 12 in. rock sizes with a sump upstream of the weir.

3.2 Ponds

An initial survey assessed the topography to determine the best location for Pond 3C. Based on the actual topography, the logical approach was to build adjoining ponds (primary and secondary ponds, Figures 13 and 14). These ponds were built as reservoirs or snowmelt settling ponds. The primary pond is located on a natural depression area. The excavator (with a bucket for digging materials and ripper and hammer, also called a hydraulic hammer or pecker, attachments for breaking the hard layer) was used for digging the pond. Building this pond included digging out a portion of the natural depression (Figure 13). Digging commenced on 12 December 2015 and continued for several days, encountering alternating layers of fractured basaltic boulders and gravelly sand deposits over massive ice layers. The fractured basaltic boulders and gravelly sand materials extracted in the pond area were placed and compacted to build up the top berm. Some boulders and rocks were set aside for building a French drain type of dike in the outlet. Downstream, the outlet is the secondary pond (Figure 14). The secondary settling pond was built to buffer the excess snowmelt from the upper pond. Constructing both the primary and secondary ponds for Pond 3C took 46 equipment hours, including final adjustments (Figure 15).

Figure 13. Digging the primary pond at Pond 3C.

Figure 14. Digging the secondary pond.

Figure 15. Fine-tuning the ponds. The *left* photo is secondary pond, and the *right* photo is the primary pond.

Figures 16 and 17 show the final layout of the ponds. A final survey after fine-tuning the ponds collected information about the final layout to determine the elevations, areas, and volumes. Table 3 summarizes the final sizes of the ponds, which were relatively shallow. The primary pond had a total volume of approximately 21,000 cu ft. The secondary pond covered half the size of the primary pond with a total volume of 11,000 cu ft. The total capacity was approximately 32,000 cu ft, which was significantly smaller than the minimum design for Pond 3C by a factor 15. The rationale for the limitations included that (1) the area had insufficient space to build the designed size; (2) the equipment had other projects to support and so had limited availability for this project; (3) and it was treacherous to dig deeper in ice and hard rock on unstable ground, creating safety concerns for the equipment (sliding and traction) and operator. The ponds built for Pond 3C will serve as experimental settling basins to determine whether the ponds will retain the snowmelt and whether the berm and spillway will hold up and attenuate the flow.

For Pond 2C, an exploratory digging during austral summer 2015–16 examined subsurface conditions and materials of the area. The materials extracted in a 20 by 30 ft, 10 ft depth, area were primarily solid ice. O&M staff were cautious and uncertain that building a pond in that the location would be stable given the topography (slope) and significant amount of ice in the ground. This would require significant digging and landscape changes to build a pond in the general vicinity.

Figure 16. Perspective view of Pond 3C showing the final layout of the primary pond (*right*) and the secondary pond (*left*).

Figure 17. Contours of the final layout of the primary pond (*right*) and the secondary pond (*left*)

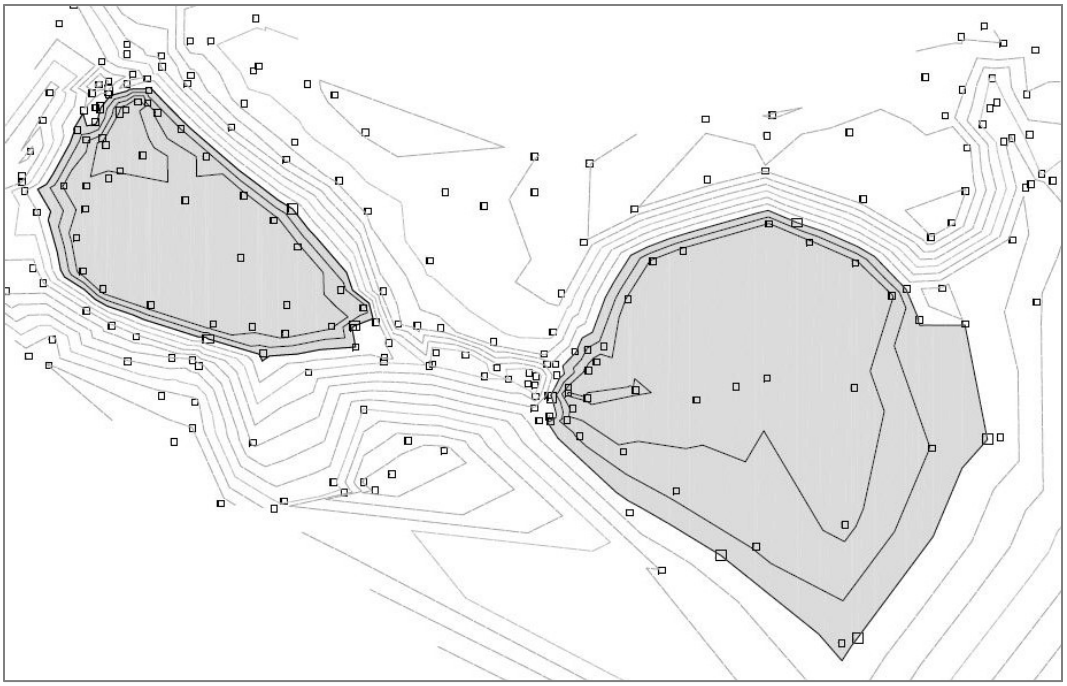


Table 3. Summary of Pond 3C final dimensions.

Pond 3C	Bottom Elevation (ft)	Top Elevation (ft)	Area (ft^2)	Average Volume (ft^3)
Primary	399	402	12,000	21,000
Secondary	395	398	5150	11,000
Total Capacity			17,150	32,000

4 Weir Performance Results

4.1 Flow and sediment collection

Within a few days after the installation with light and moderate runoff, the rock weirs slowed down the flow and trapped sediments upstream of the weirs (Figure 18). The water level (or stage) reached below the height of the weir; and as the air temperature reached the freezing point, the water froze at that level. The unanchored wooden weir performed similarly to that of the rock weirs, trapping sediments and reducing the flow (Figure 19). The geotextile fastened on the unanchored weir slowed down the flow tremendously, trapping not only the sediments but also wooden debris. The geotextile was removed by mid-December because the water undercut and weakened the bank, eroding the soil on the edges when the runoff was high. The anchored wooden weirs performed well when light to moderate runoff flowed (Figure 20).

Trapped sediments upstream of the weirs were regularly scooped out with the excavator (Figure 21) and spread on the top side of the banks. Most of the runoff on the drainage channels from the first week of December 2015 to mid-December 2015 came primarily from subbasin 3. Thus, the drainage channels for subbasin 3 runoff flowed continuously at a moderate rate. Runoff from subbasin 2 that flowed in the drainage channel along Gasoline Alley was relatively light from the first week of December 2015 to mid-December 2015 (Figure 20). At that time, the snowmelt for subbasin 2 was accumulating in the existing natural depression/lake at the lower ice field.

Figure 18. Water stage and sediments upstream of the rock weirs during light flow.

Figure 19. Water stage and sediments upstream of the unanchored wooden weir.

Figure 20. Water stage and sediments upstream of the anchored wooden weir.

Figure 21. Typical amount of sediments collected from the weirs.

4.2 Limitations and exceeding the capacity

During peak and heavy runoff periods, failure in the form of erosion occurred along the bank edges next to the weirs, the massive water force eroding the material on the unprotected banks. Another reason for this failure was that the ice in the banks melted, creating space for water to flow. Bank instability was a common occurrence when excessive amounts of runoff passed through the weirs; especially banks with no stone lining or riprap were unprotected and vulnerable to failure (Figure 22).

Figure 22. Example of a collapsed bank adjacent to the weir when excessive amounts of runoff occurred.

The anchored wooden weirs held up during an excessive runoff period. There was a surge of runoff from subbasin 2 on 18 December 2015, and it overwhelmed the drainage channel along Gasoline Alley (Figure 23). The rock pile shown on the side of the road in Figure 23 was the sediment excavated from the channel upstream of the wooden weir, and the sediments kept building up at this level of flow. By midday, the water had flowed over the weir; and a significant amount of rocks and sediments were trapped in front of it (Figure 24). At this point, the heavy-equipment operators were building a temporary berm by piling stones and rocks along the road to make sure the water stayed in the drainage channel. The excavator continued to remove the stones and rocks trapped in the weirs and deepened the channel.

The runoff from subbasin 3 and subbasin 2 (the flow discharged along Gasoline Alley) merged into the main channel along the Main Road, exceeding its capacity (Figure 25). With this extreme level of runoff, the wooden weir was buried in water, sandwiched between sediments and rocks, and considered nonfunctional. The excavator continued placing big rocks along vulnerable banks to minimize significant erosion and scooping sediments out of the channel. The main culvert was full with water and potentially blocked with debris and rocks; the road was purposely dug out, opening a diversion route for excess water. (There was an outburst of so much water that it looked like rapids). The excessive runoff period continued into the following day (19 December 2015) and gradually dwindled within a couple of days.

Figure 23. Extreme runoff around 9 a.m. in the drainage channel along Gasoline Alley. The *left* image shows downstream, and the *right* image shows upstream of the weir.

Figure 24. Extreme runoff around 3 p.m. in the drainage channel along Gasoline Alley. The *left* image shows upstream, and the *right* image shows downstream of the weir.

Figure 25. Runoff in the Main Road channel (the *top* picture was taken around 9 a.m., and the *bottom* picture taken around 3 p.m.).

5 Lessons Learned and Recommendations

The performance factors of the weirs were assessed in terms of constructability and functionality based on the austral summer 2015–16 runoff conditions and the current state or existing capability of the drainage system. The constructability ratings address the materials preparation, setup and site-placement time, the ease of construction, and the materials used. The functionality of the weirs are characterized according to the range of operational performance conditions of the runoff as summarized in Table 4.

Table 4. Performance criteria for the weirs.

	Constructability			Operational Conditions		
Type of Weir	Materials Preparation and Setup and Site Placement Time	Ease of Construction	Materials	Light Flow	Moderate Flow	High to Surge Flow
Anchored wooden weir	Approx. 6 hours to construct, including cutting the boards, drilling the holes on the boards, drilling the holes for the metal posts, and fastening the boards with brackets and screws to the metal posts	Simple; required a drill rig to drill the hole for the posts	Foreign: wood boards, brackets, and screws	Passed	Passed	Failed
Unanchored wooden weir	Approx. 6 hours to construct, including cutting the boards, drilling the holes on the boards, framing the boards together, and fastening together with screws for placement	Simple	Foreign: wood boards, brackets, and screws	Passed	Passed	Failed
Rock weir	Approx. 1 hour to construct with the aid of heavy equipment	Simple using local rocks; required an excavator and a loader	Local materials: Rocks and stones	Passed	Passed	Failed

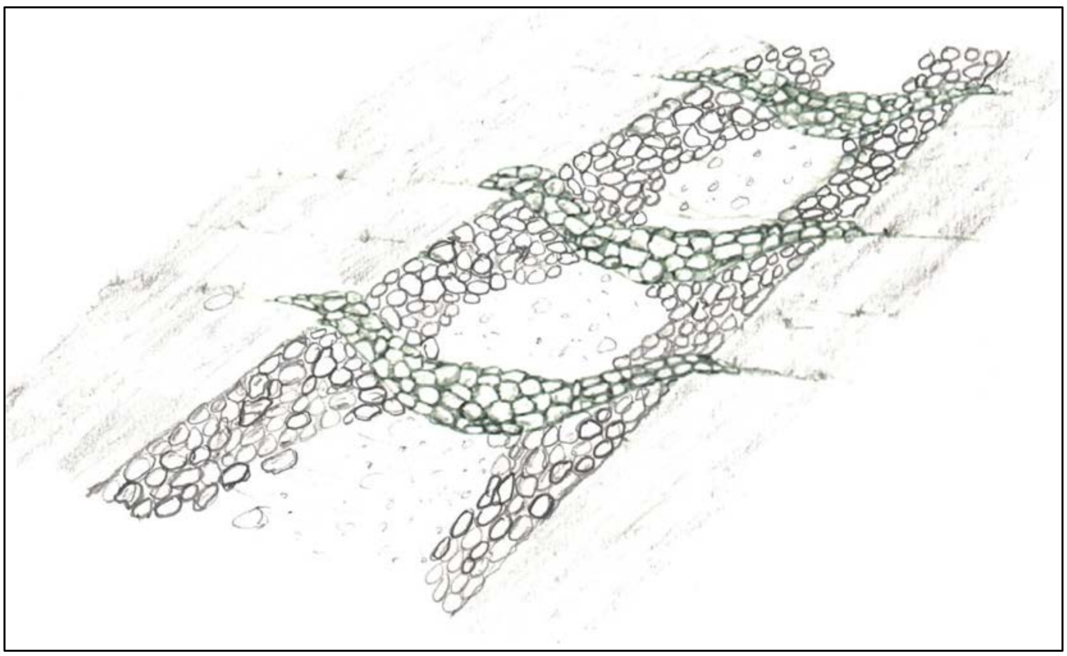
The weirs were structurally designed to withstand the hydraulic forces of a 50-year design flow by using the design parameters unique to McMurdo Station (Affleck et al. 2014c). Under normal conditions when flows were light to moderate, the weirs performed well, collecting sediments and attenuating the diurnal flows. Despite the weirs being operationally rated as “failed” during high and surge flows (Table 4), the weirs were structurally stable and held during the 18 December 2015 flow surge. In this case, failure occurred when the excess flow eroded the banks adjacent to the weirs and the weirs became submerged. The huge amount of runoff resulted in

extreme hydraulic energy, creating massive erosion and mobilizing the sediments on instable banks where water flowed through paths with less resistance.

During the melting season when the ground starts thawing, bank soils can be highly erodible and unstable because of excessive pore-water pressure and disrupted soil structures, creating mass failures. Steep bank slopes (ranging from 30°–36°) are common at the Station. The combination of steep slopes and no structural support makes banks vulnerable to erosion and mass slides as runoff undermines the soil structure.

The banks should be stabilized and lined using gabion (where the rocks are reinforced with wires) or geosynthetics and covered with big stones and rocks to mitigate this problem (Figure 26). With the current state of drainage without a way to control snowmelt upstream, the capacity of the drainage channels is unable to handle the excessive amount of runoff.

Figure 26. Ideal design for stabilizing and lining the sides of the channels by using riprap and spacing the rock dams.



The presence of ice or debris in culverts persists, and clearing the buildup requires considerable operational attention. Some of these culverts are undersized and others are in poor conditions, both of which contribute to the

vulnerability for blocked flow. The SOP by Affleck and Carr (2014) highlights recommendations. The SOP suggested digging out culvert inlets and outlets by mid-November; removing the ice or debris in culverts, especially along major drainage channels (along the Main Road and Gasoline Alley), before the first week of December; clearing blockages in tight areas with intercepting utilities; replacing undersized and aging culverts with culverts that are durable in cold climates; using heat injection or properly installing a heat-trace system in culverts; and plugging the ends of the culverts with an actual cap (as opposed to snow) before winter hits. Although these recommendations were not comprehensive, these will contribute to improving flow and reducing erosion during runoff surges.

There are several channels located in parallel utility lines; placing and maintaining flow controls along those channels is difficult because of accessibility. In addition, there are channels along steep slopes. For these problematic channels, creating new drainage route to handle the extreme flows and merging several existing flow paths are recommended to be addressed in future improvement at the Station.

Lastly, an estimated volume of runoff of 212,758 m^3 was discharged to WQB from subbasins 2 and 3 during austral summer 2010–11, totaling 71% of snowmelt runoff from the entire watershed (Affleck et al. 2014a). Another 18% of snowmelt runoff discharge was contributed from subbasin 1. Approximately 90% of the discharge from the entire watershed went into WQB. Although the amount fluctuates from one summer to the next, a significant amount of snowmelt (approximately 70 million gallons in 2010–11) accumulated in the ponds, and this can be captured before the runoff exits and creates erosion havoc downstream due to excessive runoff. A feasibility study should be conducted to examine efficient methods to harvest and processes the excess snowmelt for local use (for drinking or for other uses).

6 Summary and Conclusions

This report described the constructability ratings of the temporary weirs, addressing materials preparation, setup and site placement time, ease of construction, and the materials used. Overall, the construction and installation of the temporary weirs were simple and required minimal time to construct. In addition, this study demonstrated the functionality of the weirs according to the range of operational performance conditions during runoff. Under normal conditions when flows were light to moderate, the weirs performed well, collecting sediments and attenuating the diurnal flows. The weirs were structurally stable and held during a significant flow surge, but weirs were considered nonfunctional under high and surge flows and failed when excess flow eroded the banks adjacent to weirs and the weirs became submerged. The huge amount of runoff resulted in extreme hydraulic energy, creating massive erosion and mobilizing the sediments on instable banks where water flowed through paths with less resistance.

Digging the ponds at site 3C was achieved with the use of the excavator. However, the final sizes of the ponds were relatively shallow and smaller than the minimum design for Pond 3C by a factor 15. The restrictions were due to a confined build space, availability limitations for the equipment, and an area too treacherous to dig deeper in ice and hard rock as the unstable ground created safety concerns for the equipment (sliding and traction) and operator. However, the ponds built at site 3C will serve as experimental settling basins to determine whether the ponds will retain the snowmelt and whether the berm and spillway will hold up and attenuate the flow. They will also be used to assess the seasonal ice buildup in the ponds.

The ground and terrain at McMurdo Station are prone to erosion during excessive snowmelt runoff. Given that there is a significant amount of runoff in a given summer, snowmelt accumulated in the ponds can be harvested and used for local purposes. This is one way to decrease erosion, reduce drainage maintenance, and minimize ice buildup in culverts.

Current practice by O&M staff at McMurdo Station, Antarctica, for drainage has gained a few improvements; this included installations of a heat-

trace system in a few culverts to melt the ice that accumulates in the winter months. O&M crew installed rock weirs again this summer (2016–17); the weirs work well although some of the weirs need refinement (DeValentino 2016). Current practice needs continuous improvements to prevent significant sediments (soil fines) and pollutants from running into WQB and McMurdo Sound. An SOP was developed based on data measurements and analyses, documented Affleck et al. (2012a, 2012b, 2014a, 2014b, 2014c), and addressed the procedural processes and steps and BMPs for operation and maintenance of the drainage system. Adoption of the SOP and BMPs requires stakeholder (National Science Foundation and Antarctic Support Contract) buy-in and designated and timely commitment of resources (equipment and staff). The SOP, BMPs, and lessons learned should continue to evolve or improve and be incorporated into the proposed redevelopment at McMurdo Station as part of sustainable practices.

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Appendix A: McMurdo Station Climate Data from Austral Summer 2000–01 to 2015–16

Figures A-1 to A-16 show the daily maximum, average, and minimum temperatures. In general, the first warm spell starts between mid- to late November and into early December. A return to a cooling trend normally begins at the end of January and into February.

Figure A-1. The daily maximum, average, and minimum temperatures for austral summer 2000–01.

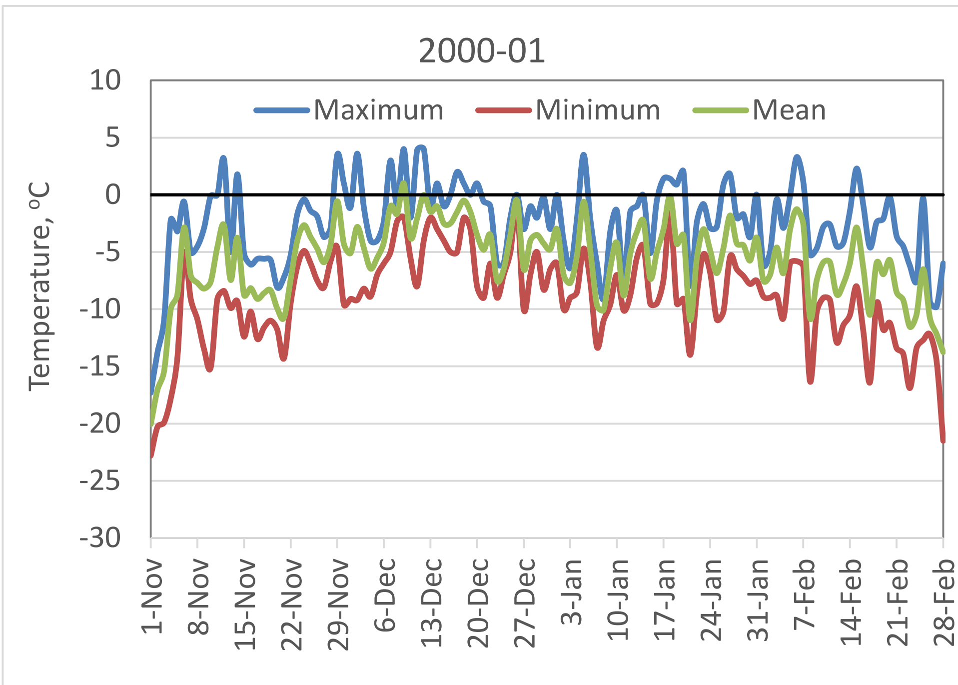


Figure A-2. The daily maximum, average, and minimum temperatures for austral summer 2001–02.

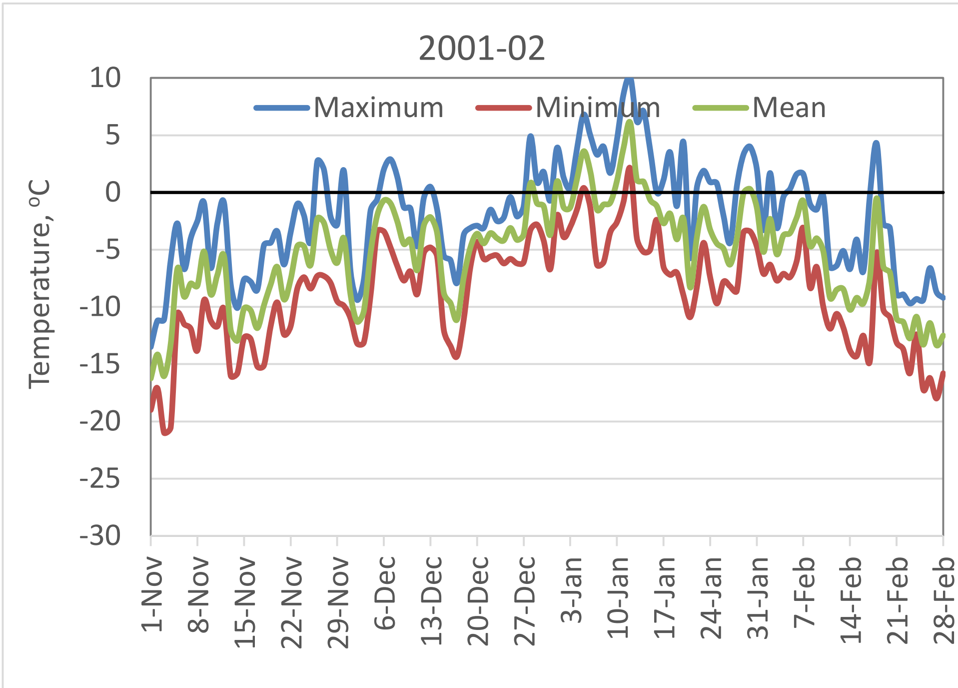


Figure A-3. The daily maximum, average, and minimum temperatures for austral summer 2002–03.

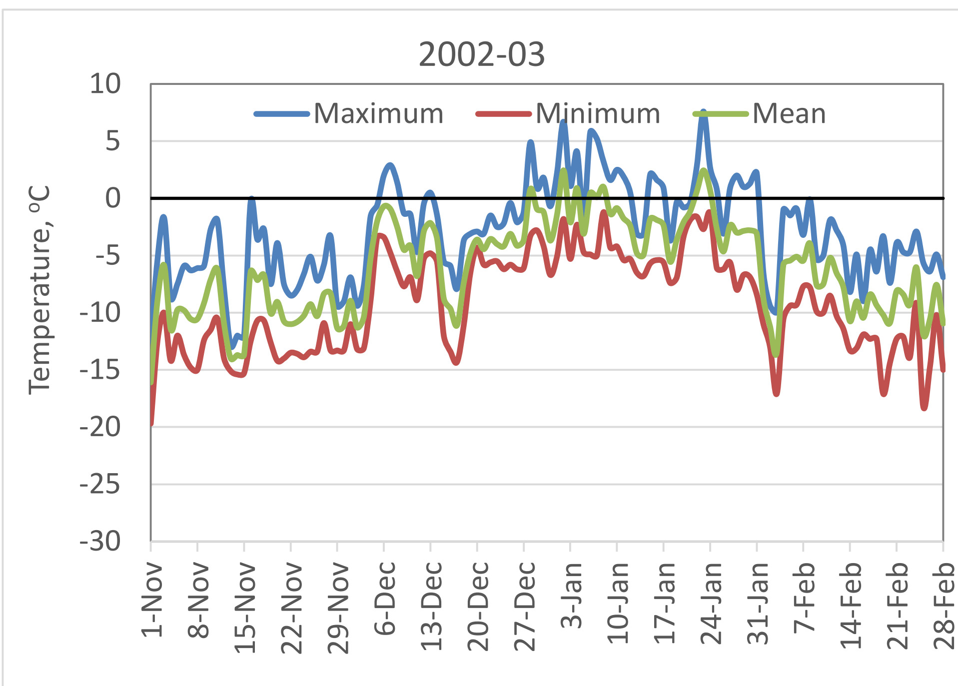


Figure A-4. The daily maximum, average, and minimum temperatures for austral summer 2003–04.

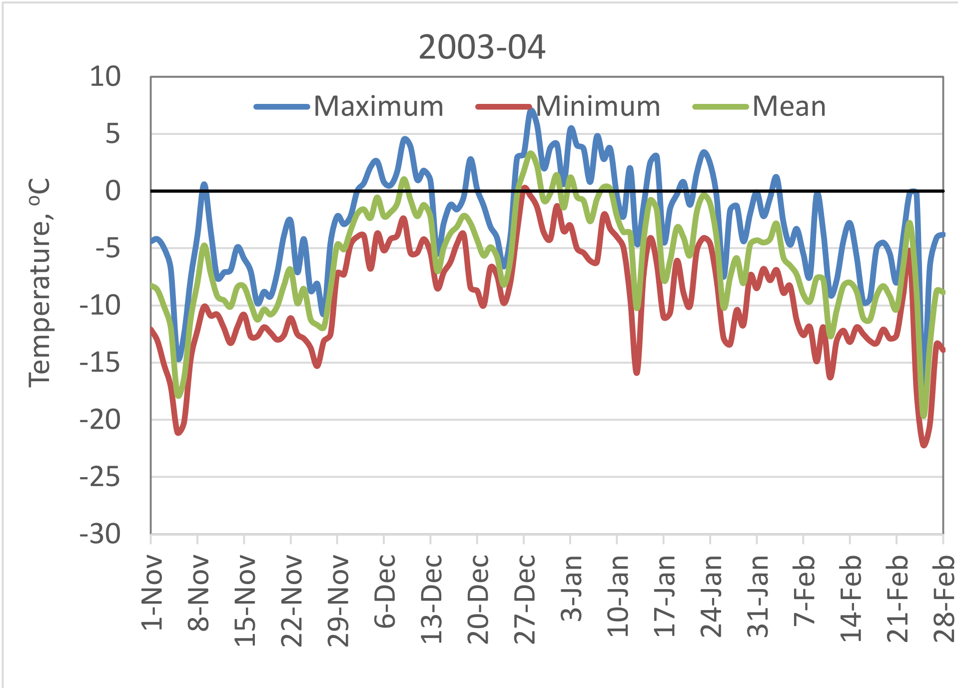


Figure A-5. The daily maximum, average, and minimum temperatures for austral summer 2004–05.

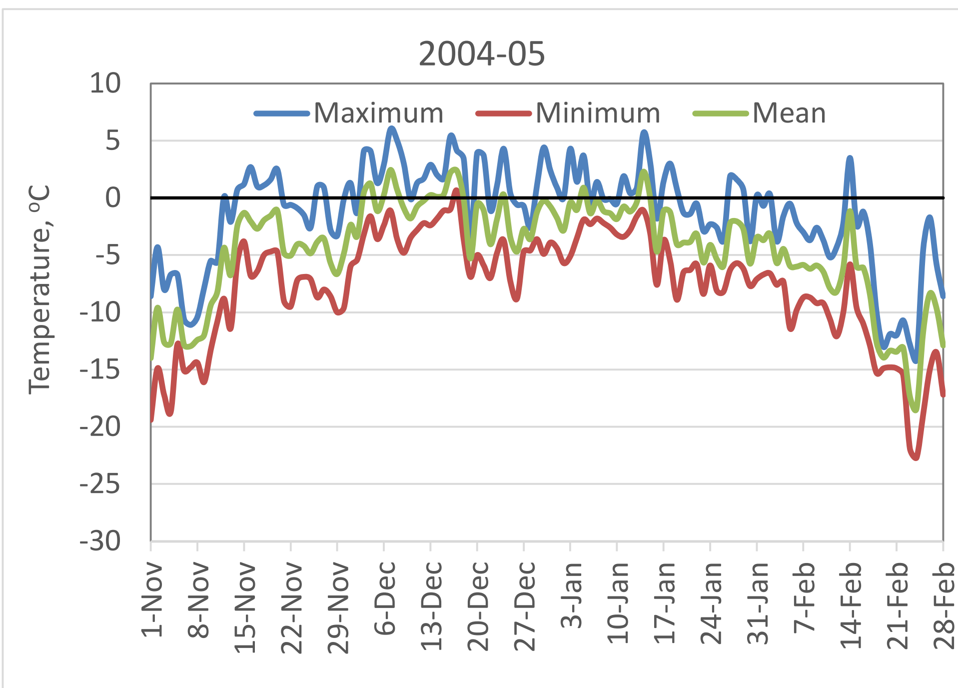


Figure A-6. The daily maximum, average, and minimum temperatures for austral summer 2005–06.

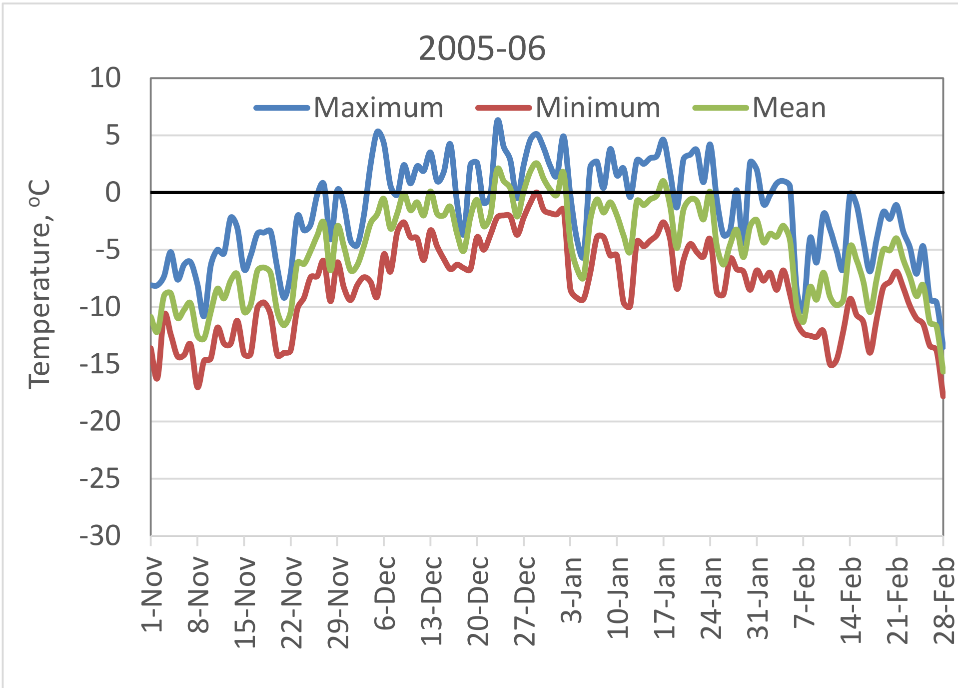


Figure A-7. The daily maximum, average, and minimum temperatures for austral summer 2006–07.

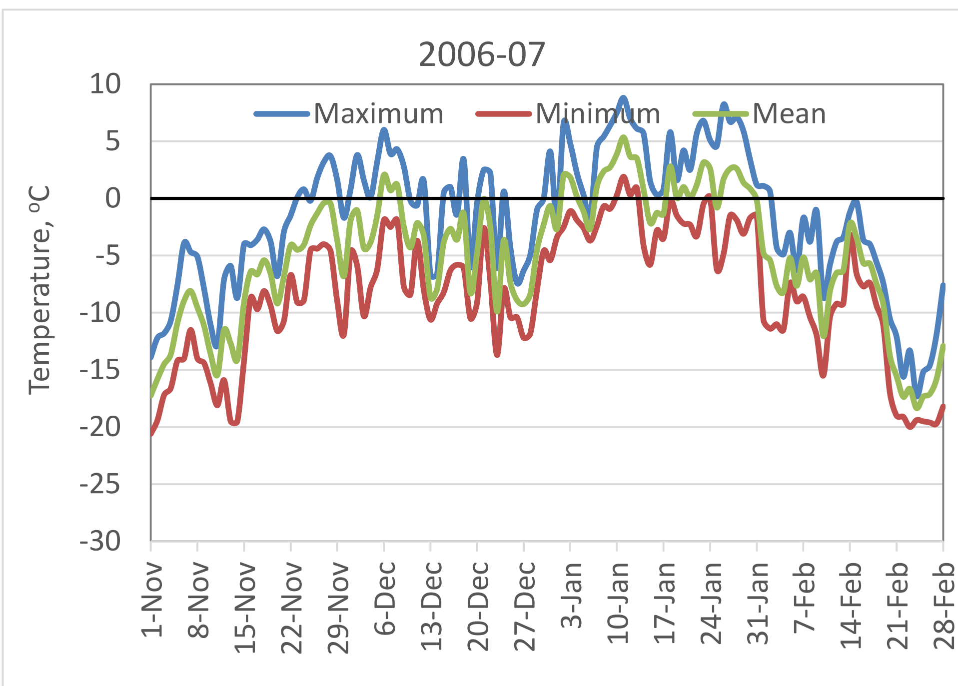


Figure A-8. The daily maximum, average, and minimum temperatures for austral summer 2007–08.

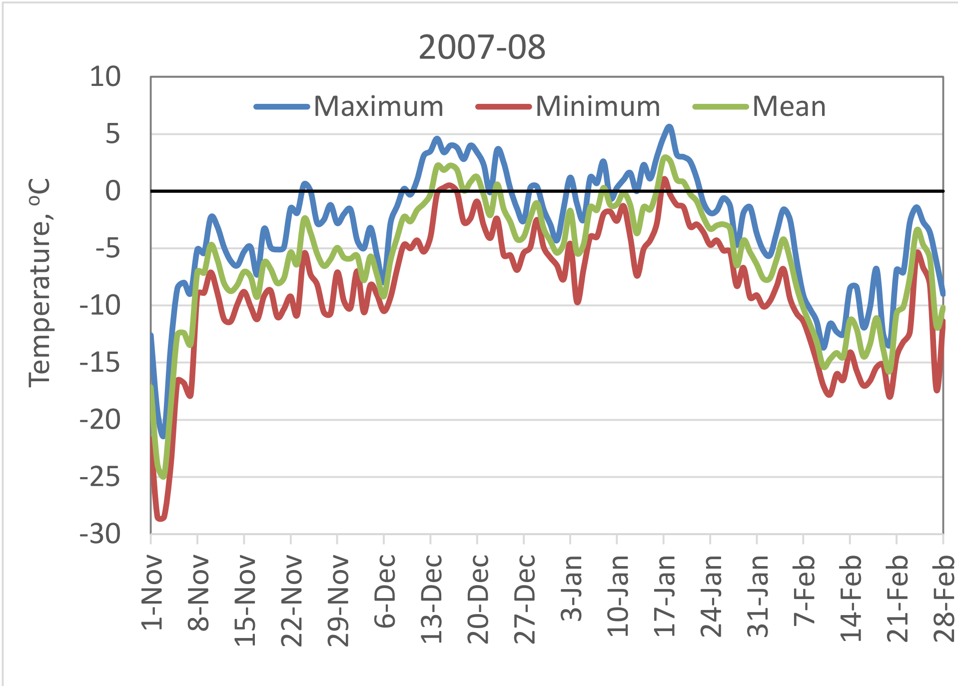


Figure A-9. The daily maximum, average, and minimum temperatures for austral summer 2008–09.

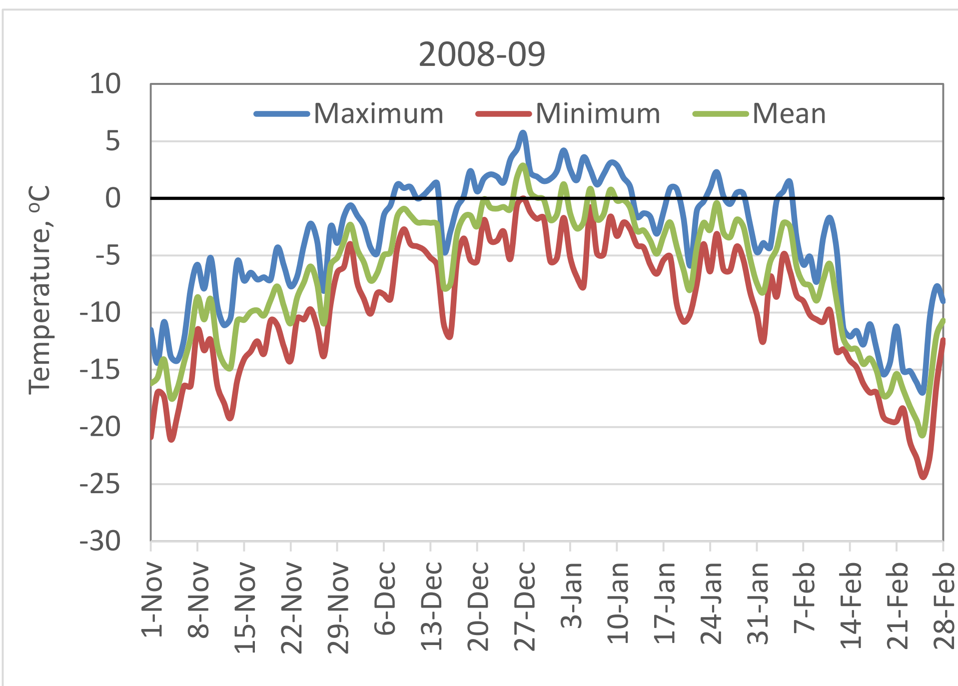


Figure A-10. The daily maximum, average, and minimum temperatures for austral summer 2009–10.

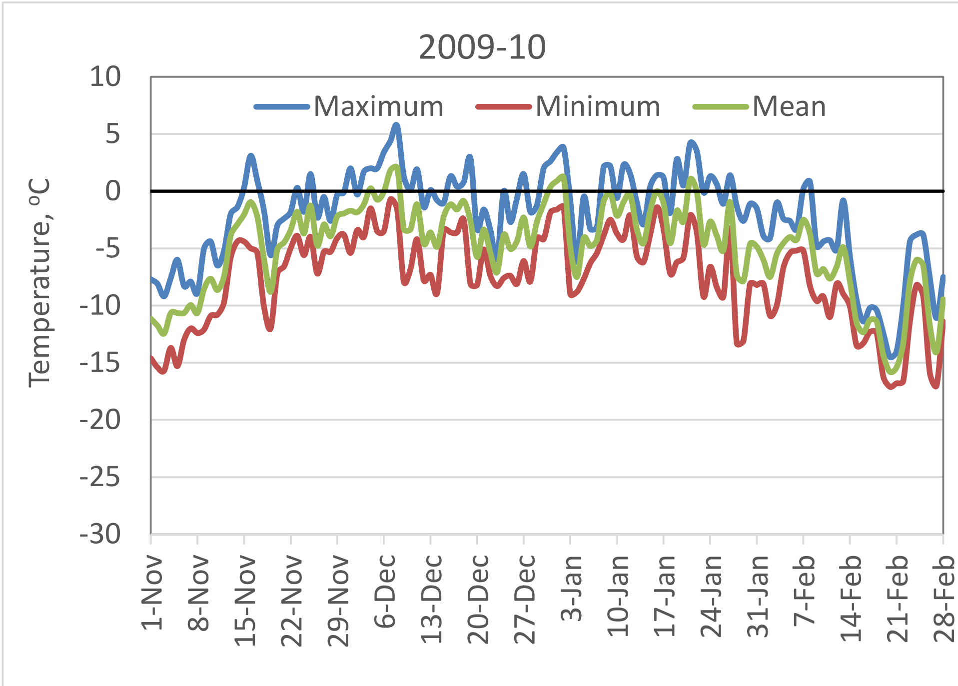


Figure A-11. The daily maximum, average, and minimum temperatures for austral summer 2010–11.

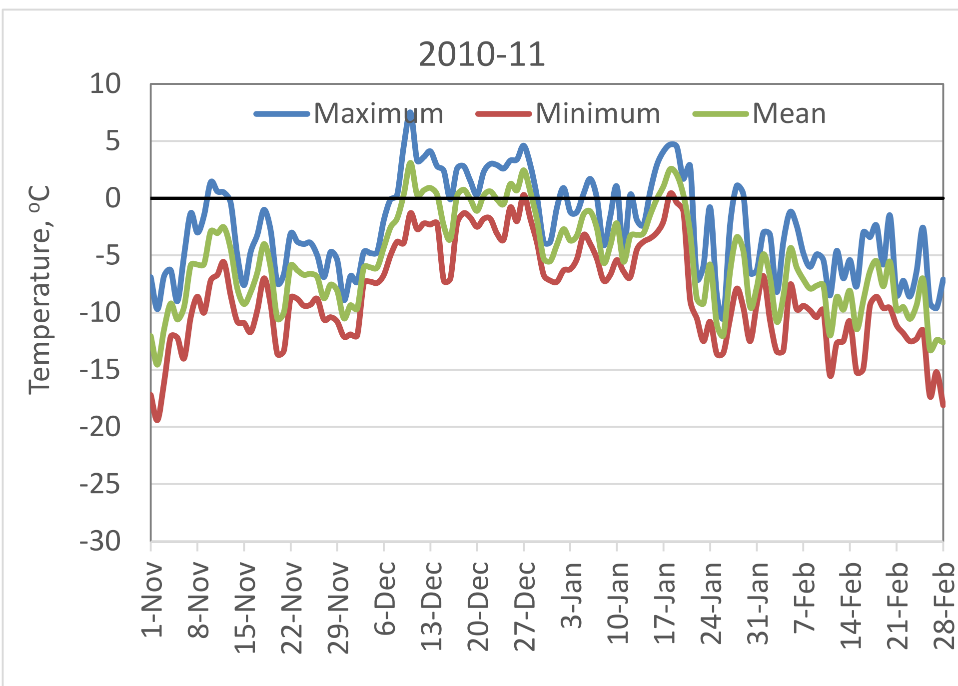


Figure A-12. The daily maximum, average, and minimum temperatures for austral summer 2011–12.

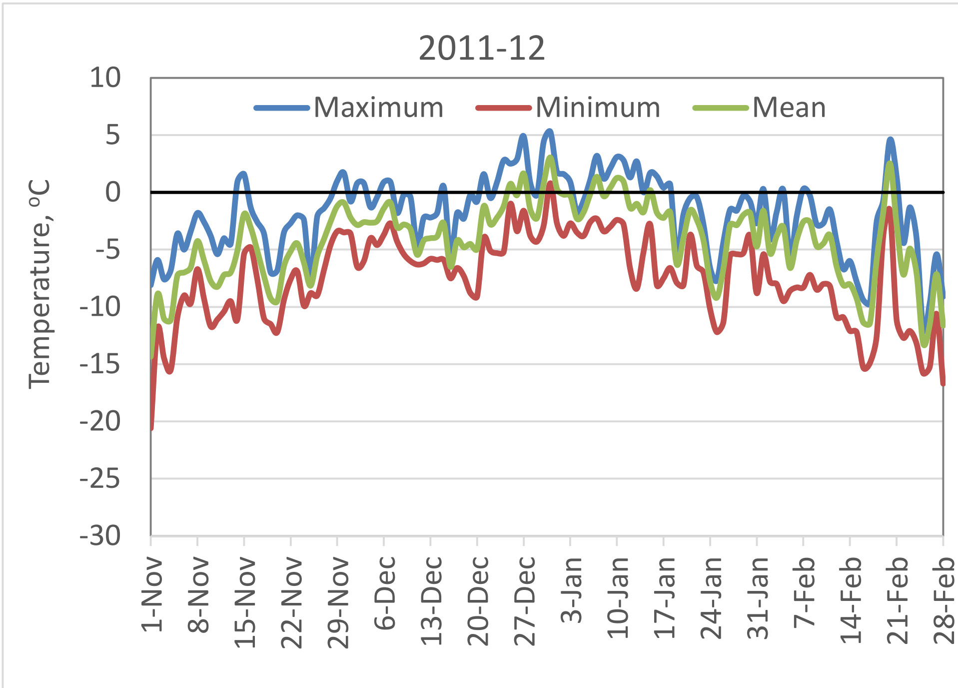


Figure A-13. The daily maximum, average, and minimum temperatures for austral summer 2012–13.

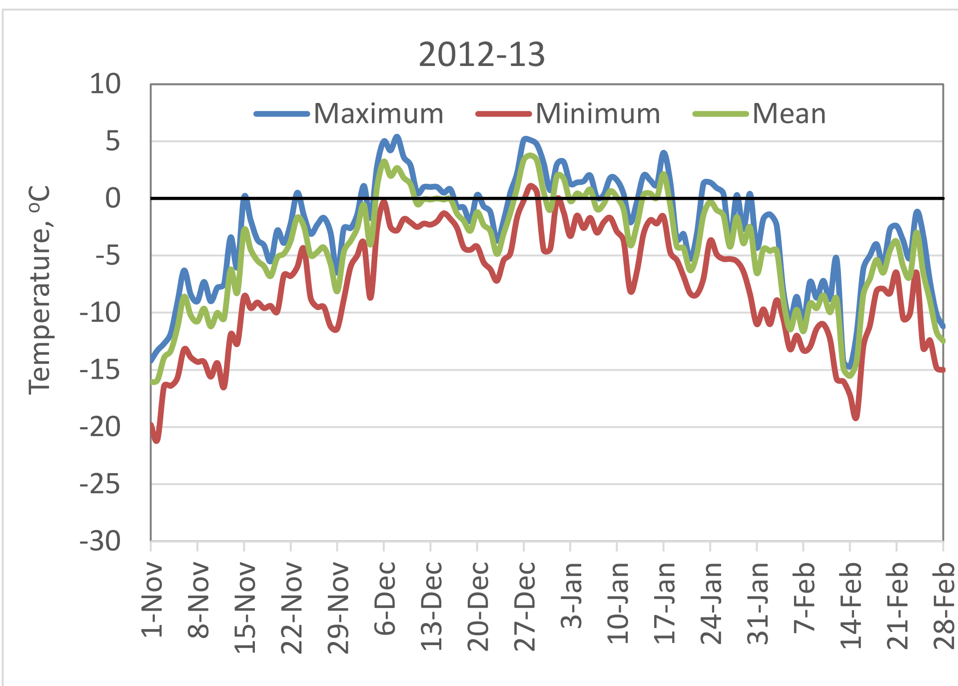


Figure A-14. The daily maximum, average, and minimum temperatures for austral summer 2013–14.

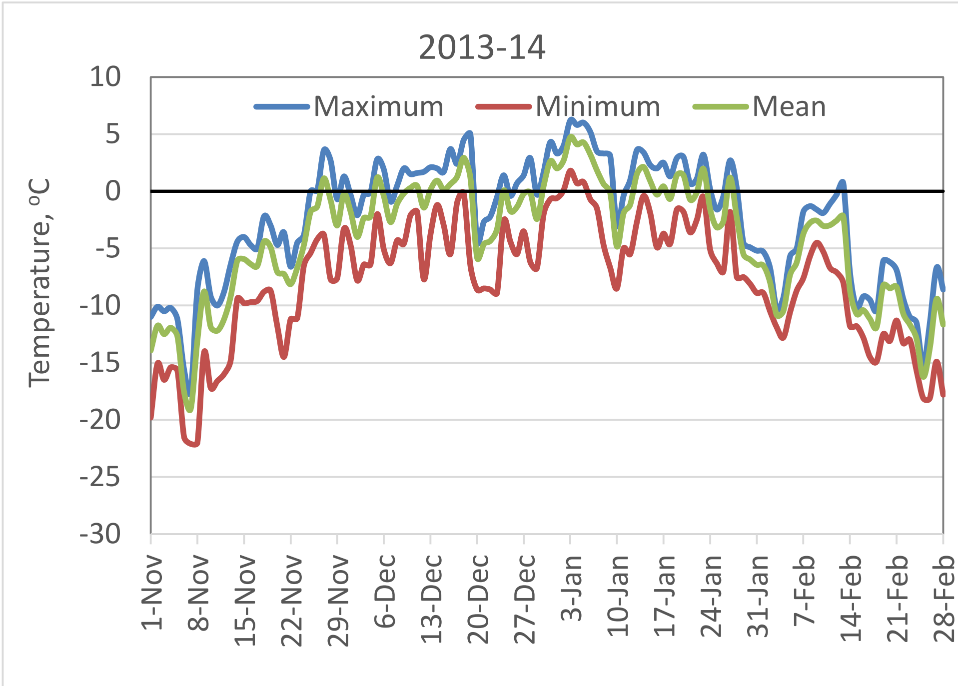


Figure A-15. The daily maximum, average, and minimum temperatures for austral summer 2014–15.

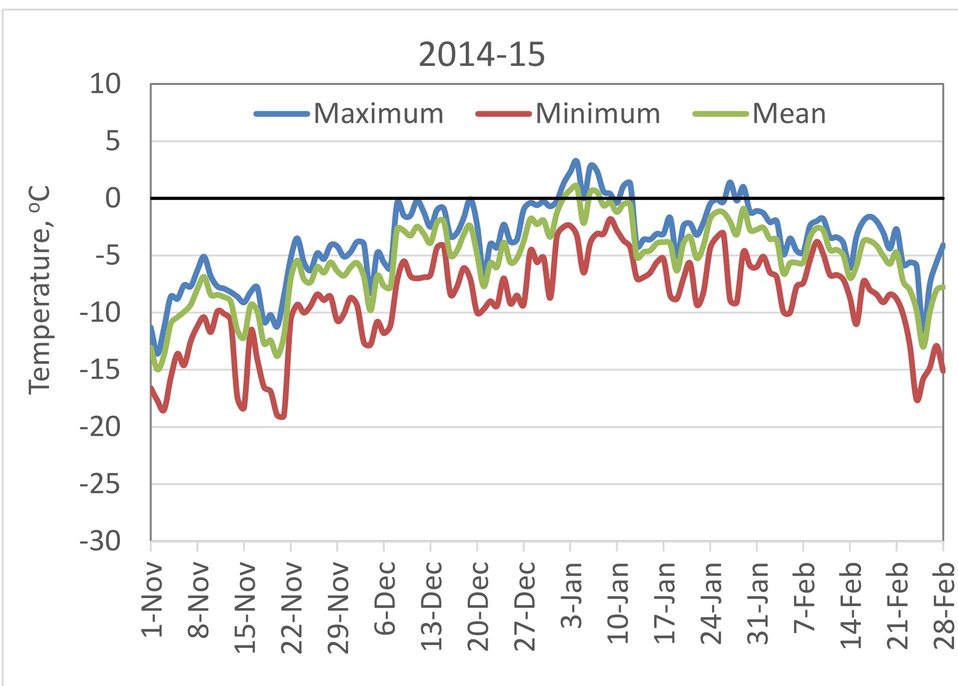
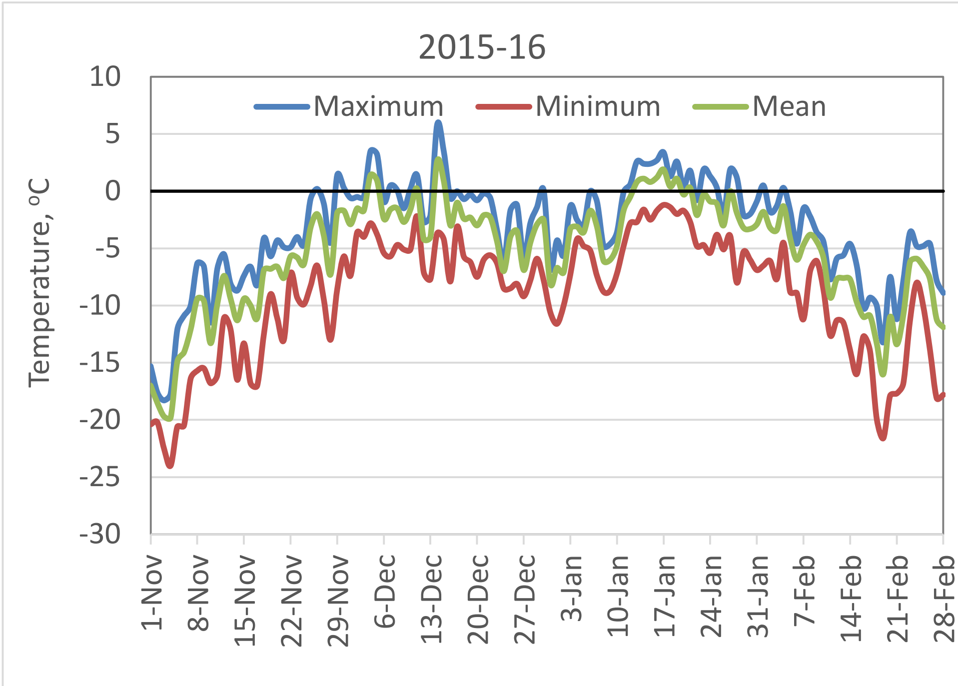


Figure A-16. The daily maximum, average, and minimum temperatures for austral summer 2015–16.



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14. ABSTRACT The snowmelt runoff during the austral summer at McMurdo Station is diurnally and seasonally variable. The variability is caused by a dynamic process in which the flow fluctuates daily and seasonally in response to solar and temperature input, melting the snow and glacier ice in the watershed. The current state of drainage at McMurdo Station has operational challenges and environmental impact when incidents of extreme flow occur. A surge of massive amounts of runoff downstream overwhelms both the drainage-system capacity and operational personnel and mobilizes sediments and transports potential and known contaminants downstream. The purpose of this project was to demonstrate the feasibility and use of flow-control systems (including wooden and rock weirs) to attenuate flow in drainage channels and digging settling basins to contain snowmelt. When runoff was light to moderate, the weirs performed well, collecting sediments and attenuating the diurnal flows in the channels. However, the weirs became nonfunctional under high and surge flows. Experimental settling basins were constructed to determine whether they will retain the snowmelt and whether their berm and spillway will hold up and attenuate the flow. Moreover, this report highlights best management practices and lessons learned for sustained elimination of erosion and for reduced drainage-system maintenance.					
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